SMART MESOFLAPS FOR AEROELASTIC TRANSPIRATION FOR SBLI FLOW CONTROL

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Abstract
This multi-disciplinary research project investigates the capability and performance of a novel concept termed Smart Mesoflaps for Aeroelastic Transpiration (SMAT), which will provide mass and momentum transfer to control shock/boundary-layer interactions (SBLIs). Such flow control can be critical for supersonic mixed-compression inlets which have impinging oblique-shocks. The SMAT concept consists of a matrix of small flaps (sub-millimetric in thickness) covering an enclosed cavity. These flaps are designed to undergo local aeroelastic deflection to achieve proper mass bleed or injection when subjected to impinging oblique shocks. The resulting system is designed to efficiently reduce and prevent flow separation caused by SBLIs. The expected pay-offs in aircraft performance are a lighter, smaller, and more robust bleed system for supersonic inlets with reduced compressor-face inlet distortion.

This study closely integrates experimental and computational investigations of the SMAT concept in relevant SBLI flowfields. The numerical studies employ an aeroelastic finite element code to investigate the physics between the supersonic turbulent boundary layer, the subsonic cavity flow, and the deforming mesoflaps. These analyses are coupled to advanced shape-optimization techniques such that mesoflap design can be optimized for a given flow condition. The resulting methodology is being used to guide the fabrication of the mesoflaps using both conventional metal alloys and smart materials. Aerodynamic experiments will be conducted for various flap arrays to investigate fundamental flow phenomenon and measure aerodynamic performance.

Rationale for the Proposed System

With respect to internal flows, most high-speed (above Mach 2) military aircraft employ active bleed control for their engine inlets, which requires ducting of the bleed flow to an external surface (Gridley and Walker, 1996). To improve the aerodynamic performance of such inlets, there are significant advantages if one can employ passive transpiration, i.e. combine both bleed downstream of the shock with flow injection upstream of the shock. In general, there are two primary benefits of passive transpiration (vs. active bleed): (1) the upstream blowing can allow additional thickening of the boundary layer upstream of the shock interaction, producing a system of weaker shocks, which thereby reduces wave drag and the intensity of the shock footprint; and (2) the system does not require pumping power or ducting to or from the

transpiration cavity. However, these beneficial factors are generally accompanied by three disadvantages: (1) transpiration rates are typically insufficient for boundary layer control (Bur *et al.* 1998); (2) the general case requires holes or slots that are normal to the transpiration plate, but this geometry is significantly less effective than angled holes for bleeding (Harloff and Smith, 1995); and (3) it can yield increased drag at lower Mach numbers, e.g. when no shock or weak shocks are present (Raghunathan, 1988). The SMAT system proposed herein aims to alleviate these three traditional limitations, while maintaining the two primary advantages of conventional passive transpiration.

SMAT Concept

The SMAT concept consists of an enclosed cavity chamber below a matrix of mesoflaps. The goal of this system is to efficiently reduce and prevent flow separation caused by SBLI, thereby improving the resulting downstream boundary layer characteristics. The flaps locally deflect in a cantilever mode due to the aerodynamic pressure distribution on them to achieve appropriately angled bleed and injection, i.e. they are aeroelastically smart. The system is expected to have optimum aerodynamic performance for flaps that are 300 to 700 μm in thickness (consistent with the sonic thickness of the incoming boundary layer), with flap aspect ratios (length to thickness) of about 10. The resulting small physical flap deflections will allow a balance between limited flow obstruction by the flaps (to avoid significant entropy production) and sufficient mass flow capture (to provide sufficient flow transpiration).

Figure 1 describes the SMAT concept where the mesoflaps are *exaggerated in size* for illustration. Under no-shock conditions, e.g. subsonic flow, the streamwise pressure distribution on the flaps is essentially constant such that negligible flap deflection or transpiration is induced (Fig. 1a) thus avoiding the "roughening" of the surface caused by conventional transpiration holes or slots . Figure 1b shows the system for the conditions of an oblique shock impingement which induces a strong streamwise pressure variation. The flaps upstream of the reflection will deflect upwards allowing flow injection angled into the boundary layer. Similarly, the flaps downstream will deflect downward to allow angled bleed from the boundary layer into the cavity. By constructing the flaps in a matrix in both the spanwise and streamwise directions, such deflections can accommodate variations in both streamwise position and sweep angle of the impinging shock. In summary, the proposed SMAT concept retains the aerodynamic and acoustic advantages of conventional passive-transpiration while featuring the following advantages: (1) it can retain the self-contained simplicity of a passive transpiration system and does not require active suction ducting; (2) it can improve the transpiration flow rates via appropriately-angled bleed and injection since it can accommodate variable streamwise position and sweep angle of reflecting or glancing shocks; and (3) it can provide improved aerodynamic efficiency under subsonic or supersonic *no-shock* conditions, since the flaps would close and yield a smooth flat surface.
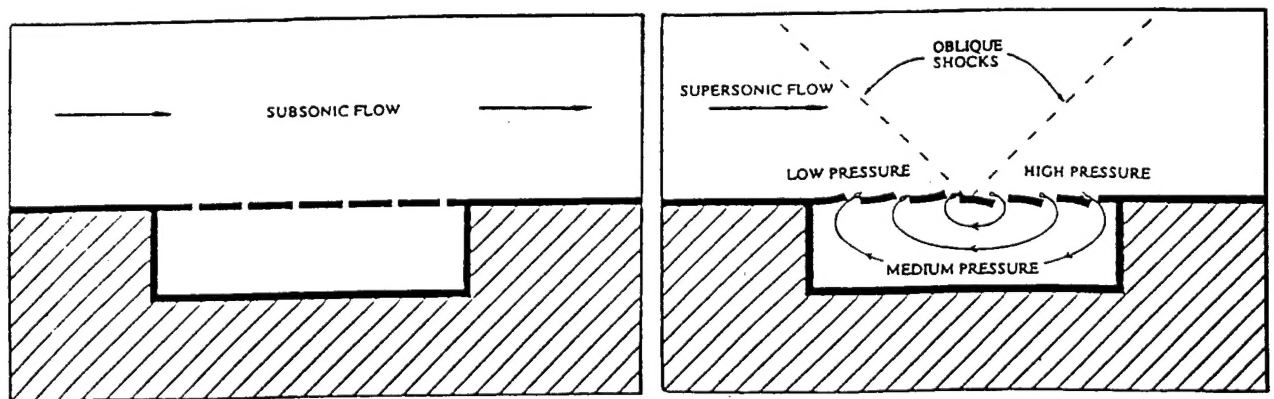

Fig. 3 SMAT system with mesoflaps *exaggerated in size* for (a) subsonic flow and (b) supersonic flow with impinging oblique-shock

Computational Approach

The basic objective of the computational part of the proposed project is to construct and validate a model of the aeroelastic system to investigate the fluid/structure interaction physics, and to enhance the design of the system by combining these simulations with recent advances in design optimization. The proposed research will combine the fully compressible turbulent flow equations with a detailed structural resolution of the internal flap structure to provide high-resolution stress, strain, and displacement fields for individual mesoflaps. This combination of Computational Fluid Dynamics (CFD) and Computational Solid Mechanics (CSM) has been integrated into a single-code.

Aeroelastic Methodology and Initial Simulations
The CFD component of the aeroelastic methodology is based on the state-of-the-art finite element code NSU2D (Mavriplis, 1991). The finite element scheme makes use of multigrid techniques and an unstructured fully adaptive mesh. The compressible turbulence model to be employed is the Spalart-Allmaras model, which has been shown to robustly simulate boundary layers, free shear layers, and confluent boundary layers with flow compressibility (Lee *et al.* 1998). On the structural side, the finite element code (PLANESTR2D) assumes conventional linear kinematics, although large deformation capabilities will be incorporated over the course of this investigation. A schematic representation of the current algorithm used to model the aeroelastic design problem is shown in Fig. 2. The current methodology employs a loosely coupled approach (Löhner *et al.* 1995) to simulate the fluid/structure interaction, since the flow field is hyperbolic whereas the structural field is elliptical.
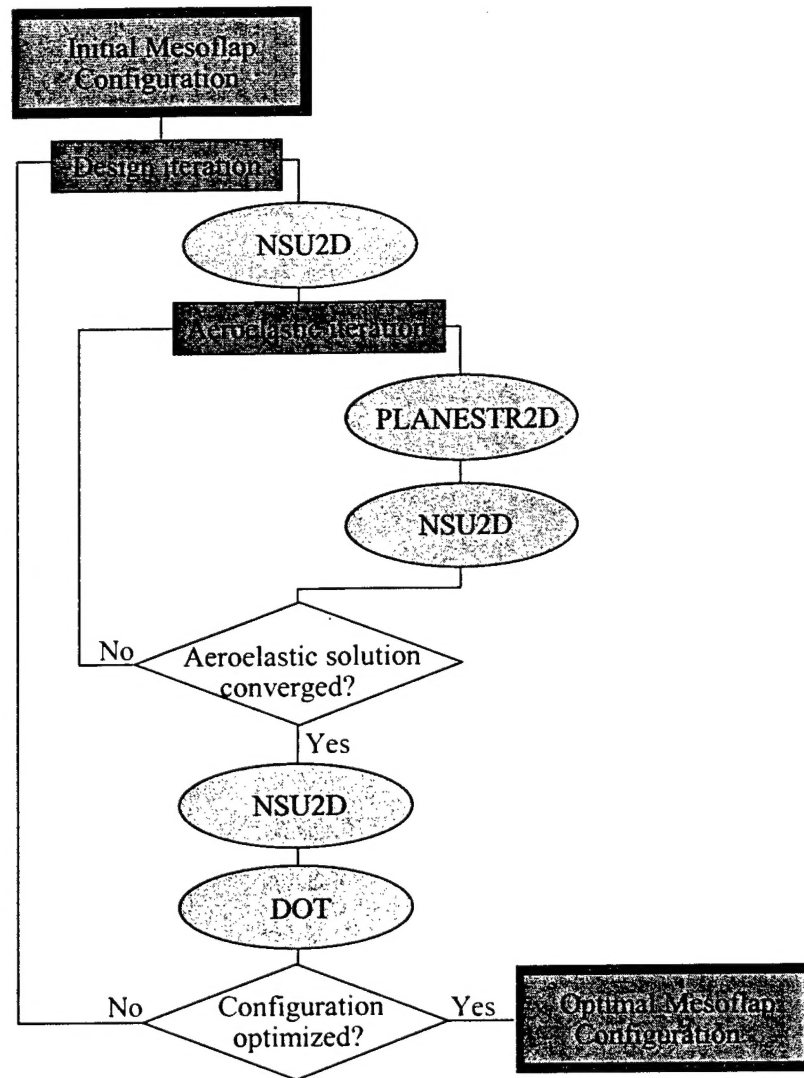
Fig. 2. Schematic of aeroelastic simulation and optimization algorithm.

To illustrate how flow transpiration is achieved with the mesoflap concept, a series of initial inviscid aeroelastic simulations has been conducted based on the inner-loop portion of Fig. 2. Figure 3. shows the Mach number contours near the mesoflaps and in the cavity below. The test conditions are for a six-flap system at Mach 2 upstream flow conditions subjected to an oblique-shock which impinges near the center of the mesoflap system. The first three flaps are aeroelastically deflected upward (due to the higher cavity pressure below) resulting in a tangentially injected flow. The last three flaps are deflected downward due to the shock-induced pressure rise. This downward deflection serves to efficiently remove most of the low-speed portion of the flow just above the flaps (note the nearly complete reduction of a wall normal velocity gradient just downstream of the flap system). From the velocity vectors (not shown), one may also note the significant high-speed recirculation within the cavity indicating high mass-transfer, which is critical to achieve sufficient transpiration for SBLI flow control.
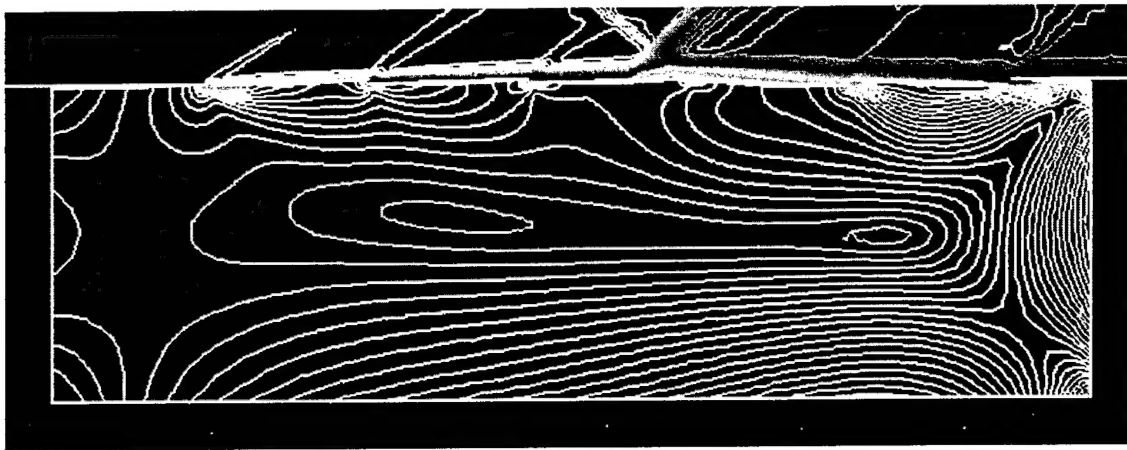

Figure 3. Plot of the Mach number contours for aeroelastically deforming six-mesoflap transpiration system at Mach 2.

Shape Optimization for Smart Mesoflaps
Using the finite-element based aeroelastic code, the outer design loop of Fig. 2 will be addressed using shape optimization. The optimization methodology will then be used to design the flaps so as to maximize the "health" of the boundary layer downstream of the interaction, while satisfying constraints on the flap integrity. This problem will be solved by nonlinear programming methods which require sensitivity information to traverse the design space in an efficient manner and to verify the optimum (Tortorelli and Wang, 1993; Michelaris et al. 1995; Wang et al. 1996). The coupled nature of the analysis will necessitate the use of Multi-Disciplinary Optimization techniques (Tortorelli, 1993).

Experimental Approach
An experimental program to address the manufacturing, static-load and aerodynamic-load aspects of the SMAT system is critical to the success of the proposed research. The issues to be investigated include: small-scale fabrication of the mesoflaps with conventional alloys and smart materials; bench-top testing to fully characterize the static-load performance and the material properties; wind tunnel testing to evaluate aerodynamic performance (the ability to

remove significant recirculation regions and/or unsteadiness caused by the SBLI) and material/structural performance (ability to withstand supersonic shear loading, and aerodynamic flutter, as well as ability to retain actuation repeatability and stability). The study will take advantage of two state-of-the-art research facilities at UIUC: the AAE Composites Manufacturing Lab and the MIE Supersonic Wind Tunnel Lab.

<u>Mesoflap Configurations</u>

After tests with conventional metal alloys, the flap systems are to be fabricated with shape memory alloys. Shape memory alloys (SMA) are materials that can "memorize" a shape and return to it after repeated thermo-mechanical cycling and can have the important property of *pseudo-elasticity* . This will allow us to design the mesoflaps to operate in passive actuation, for which the flaps will open upon reaching the critical martensitic transformation stress. This mode of actuation has many inherent advantages: (1) no external power supply is needed to achieve actuation, (2) actuation reliability is high since the material responds directly to external forces, and (3) complexity and cost of manufacturing are reduced. Using proper aeroelastic and SMA tailoring, the flaps can be designed to achieve a near optimum angled transpiration for a range of shock strengths at a given upstream flow condition. The alloy to be used in this investigation will be a nickel-titanium alloy (nitinol). The martensitic and austenitic start and finish temperatures will also be measured using a specially designed testing apparatus in the UIUC Composites Manufacturing Lab (Hebda & White, 1995). After materials testing has been completed, the single-flap configurations will be fabricated in-house at UIUC for static-load testing with an Instron 1331 servo-hydraulic test frame. Use of smart materials in the flap construction can allow the flap deflections to be tailored for optimum performance. For example, they can be designed for critical stress levels, thereby ensuring little roughening of the cavity surface for weak shock conditions which require no transpiration.

<u>Supersonic Wind Tunnel Experiments</u>

The wind tunnel experiments to be completed at UIUC are intended to provide experimental evaluation of the boundary layer control strategy and shock unsteadiness of the SMAT concept for an impinging oblique shock interaction configurations. The initial experiments will be conducted in a supersonic wind tunnel that has a test section Mach number of 2.5, and has been used extensively in previous studies of supersonic base flows (Amatucci *et al.* 1992; Smith & Dutton, 1996). The tunnel is currently being modified to include a wedge on the upper wall to generate the oblique shock that impinges on the fully developed turbulent boundary layer over the lower solid wall or mesoflaps. This particular SBLI test condition has been chosen because the no-shock case has been studied for induced roughness with a variety of bleed plates (Laurendeau, 1995) and because the no-transpiration case (solid-wall) yields flow separation (Willis *et al.* 1995). The primary diagnostic techniques to be utilized in the aerodynamic mesoflap experiments are digital spark-shadowgraph photography/cinematography, pressure-sensitive paint, laser Doppler velocimetry, and acoustic transducers (all techniques which have been developed/employed for supersonic flow measurements at UIUC). For the shadowgraphs, use of a high-speed (1 MHz) movie camera will allow direct evaluation of the unsteadiness of the shock-wave/mesoflap/boundary-layer interaction. The LDV will be used to document the mean velocity and Reynolds stress distributions in the boundary layers approaching and leaving the mesoflap assembly. This will allow determination of the induced roughness effect caused by the mesoflaps and their effectiveness in controlling the impinging shock – boundary layer interaction, *i.e.*, the "health" of the outgoing boundary layer. In addition, measurements of the wall shear stress of the outgoing boundary layer can be used in judging the effectiveness of the smart mesoflap system.

Expertise and Experience

The multi-disciplinary research team assembled for this project has direct and relevant experience with all aspects of the proposed work. Prof. White's expertise is in the fabrication and testing of smart materials; Prof. Geubelle's expertise is in the numerical modeling and physics solid mechanics; Prof. Tortorelli's expertise is in the shape optimization of multi-disciplinary systems; and Profs. Dutton's and Loth's expertise are in the experimental and computational understanding of supersonic separated shear flows with wall interactions. In addition, the investigators have direct experience with all the numerical and experimental techniques to be used in this proposed work.

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